Gateway Placement in LoRaWAN Enabled Sensor Networks

Batuhan Can, Halit Uyanık and Tolga Ovatman
Department of Computer Engineering, Istanbul Technical University, Istanbul, Turkey

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Abstract: This paper proposes two different approaches to be applied in gateway placement problem in LoRaWAN sensor networks. The first approach is based on finding the minimal set to contain all the coverage intersections of the sensors and the second approach is based on optimization via integer programming over the distance between the gateways and sensors. Our results show that using automated gateway placement provides significantly less number of gateways to be used.

1 INTRODUCTION

Placing gateways in a sensor network has always been a challenging problem. There is vast amount of research about this problem and different types of approaches have been considered to solve it efficiently. Gateway placement has a critical role in real-world applications of sensor networks, since it is necessary for a system to be energy-efficient and to have high quality data communication. A smart way of placing gateways can highly affect the total energy consumption of sensors.

In this paper, we propose two different approaches to solve the problem of gateway placement by grouping the sensors in a LoRaWAN enabled sensor network. One of these approaches relies on exploring the intersection of sensor coverage ranges and placing gateways on these intersections to cover the most intersection with the least number of gateways. Other approach uses mixed-integer programming (MIP) on an optimization model that try to minimize the number of gateways that fully cover the provided set of sensors.

We validate the proposed model not by using hypothetical sensor locations but by simulating the model with actual sensor positions obtained from a real-world case study: Ergene river (which is a major left tributary of the Maritsa river, flowing entirely in the East Thrace region of Turkey). All the sensor positions from the Ergene river has been pre-determined by a previous project to collect the most information-rich data about micro-pollutants in the river (see Figure 2). We run our experiments over two different simulators: ns-3 (Riley and Henderson, 2010) and LoRaPlan (Loh et al., 2021b). In ns-3, we have used LoRaWAN module to tune the low level communication properties between the gateways and the sensors. We collected transmission failure rates over ns-3 simulations. Also by running LoRaPlan simulations, we obtain RSSI levels throughout the sensor network and other basic signal properties for certain gateway placements.

Our results show that using MIP significantly decreases the number of gateways that can provide a full coverage even though it results in a degradation in communication quality. Both of these differences increase as the coverage of the gateways increase. Our study provides novel results over a realistic sensor distribution scenario in a rural environment. Proposed approaches have been validated by two different simulation environments ns-3 and LoRaPlan, and the results of these approaches are compared with manual placement.

2 RELATED WORK

Even though the underlying concepts such as internet of things (IoT), wireless sensor networks (WSN) and wireless mesh networks (WMN) may change through time, optimal gateway placement in wireless networks have been taking the attention of many researchers. Also the problem of coverage and clustering devices in wireless networks, have been considered in various studies (Abbasi and Younis, 2007)(Younis and Akkaya, 2008). Gateway placement as a cluster assignment problem can be defined as the division of nodes in a wireless network into

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clusters and finding the optimal location for the gateway in each group, so that the requirements of the network are satisfied by dividing the network into minimum number of clusters.

Various methods can be considered to find a solution to the problem of clustering. An example to such methods is a hybrid model which is the combination of three algorithms based on LEACH and K-Means (Bholowalia and Kumar, 2014). Clustering in the proposed model is done by K-Means algorithm. Another study presents an integer linear programming (ILP) formulation and a polynomial time recursive algorithm (Aoun et al., 2006), aiming to divide a WMN into minimum of number of clusters.

In gateway placement, it is crucial to satisfy the quality-of-service (QoS) requirements. These requirements can differ in different scenarios. In order to provide the bandwith requirements of the clients, three different models have been developed (Qiu et al., 2004) to find the best locations for internet access points (ITAP) and ILP is used to formulate the problem. Another study focuses on clustering the sensors in a way that the least transmission latency is satisfied (Youssef and Younis, 2007). For this purpose two genetic algorithms for the optimal gateway placement have been introduced and validated by simulating WSN. There is also a study where a MIP formulation is used in order to optimize the throughput in a WMN, and a greedy algorithm to solve the problem of gateway placement (Li et al., 2008). A formulation based on ILP is proposed to lower the cost of the network deployment by dividing the IoT devices into two groups such as gateways and lower-end tranmission devices, according to their power consumptions (Gravalos et al., 2016).

Communication of devices over long distances is costly. In order to overcome this problem LoRa, which is a Low-Power Wide-Area Network (LPWAN) technology, can be used. Ability of communicating over long distances at low power satisfied by LoRa increases the sustainability of the IoT applications immensely. A star-to-star topology is introduced in Long-Range Wide-Area Networks (LoRaWAN) architecture. With LoRaWAN, the necessity of building and sustaining a multi-hop network is discarded, since IoT devices are able to communicate in a single-hop, in LoRaWAN (Haxhibeqiri et al., 2018).

Pace of the studies on planning and setting up efficient LoRa networks has been increasing in the last few years. For example, a recent study discusses efficient gateway placement, where a formulation based on mixed-integer non-linear programming (MINLP) is presented to solve the problem for relatively small LoRa networks, whereas an approximate algorithm is proposed to set up wider networks (Ousat and Ghaderi, 2019). An approach to the problem of gateway placement as a clustering challenge is also presented, studying on a dynamic IoT scenario and aiming to find the optimal number of clusters so that the number of devices which are not able to transmit data will be minimized (Matni et al., 2020). Coefficients in a propagation model for Low-Power Wide-Area Networks (LPWANs) in a specific scenario, in which a wooded area is considered, are adjusted in (Cruz et al., 2022) in order to optimize the coverage area and minimize the number of gateways by using Evolutionary Particle Swarm Optimization (EPSO).

In (Loh et al., 2021a) the authors introduced an ILP based approach in order to satisfy the most common requirement of gateway placement - minimizing the total number of gateways considering the famous set cover problem while guaranteeing the robustness of the network and the proposed method has been simulated using real-world data of an urban environment. Aim of the o optimization model in this paper is to cover all the sensors and cluster them in a way that each group has an overall quality of data transmission above a determined threshold. Additionally this approach is simulated by using real-world data of a rural environment, in which data transmit ranges of gateway devices differs due to the topography of the terrain. Results are also evaluated and compared by using different tools and considering several metrics.

3 PROPOSED APPROACHES

Gateway placement is handled as an application of the set cover problem in most of the cases, because the common aim in placing gateways is to cover all the sensors in a network. It is obvious that a sensor network can be fully covered by assigning a gateway to each single device. However, this approach is not cost-efficient, since a gateway can cover more than one sensor. Thus, an optimization is needed to find these proper placement locations of gateways so that network can be divided into clusters, in where there is a single gateway device can transmit data with all the sensors in the cluster.

3.1 Placement by Coverage

Figure 1 shows the first approach on finding appropriate gateway locations for the distributed sensors across the Ergene river. First, a sphere which encapsulates the maximum assumed signal range of the sensors is drawn around the sensors. Second, the intersection of these spheres are taken, because if any

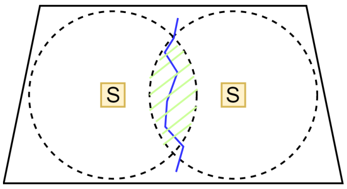


Figure 1: Intersection of signal ranges (dashed circles) are used for potential gateway (green shaded) regions.

gateway is placed within these intersections, then it is guaranteed that the communication can be established at least once. However, the intersection area is wide and therefore another step is required to find exact three-dimensional geographical location of the gateway. In this step, if there exists any river points along the intersection area, which the rivers are represented as small vector lines, then one of these points are chosen randomly. If there are no river points available, then the intersection of vertical and horizontal center of the intersection is chosen.

Number of chosen gateways can widely vary according to the coverage distance of the gateways. Due to possible inclusion of some end-devices within multiple gateway ranges, it is also possible for a sensor to broadcast its packet to multiple gateway units which can further affect the network performance. Another issue to resolve is the selection of most optimal gateway within possible optimal locations so that all sensors can be covered with minimum number of gateway units. To resolve this issue, a basic set-cover approach is applied. First the sensors and their corresponding gateways are listed in a hash-map. Then these maps are sorted in decreasing order. Lastly, sets are taken one by one until all sensors are taken at least once.

3.2 Gateway Placement by MIP

In order to find optimal locations for placing gateways, coverage distances of the devices must be considered. Transmission range of a gateway might differ due to the topology of the terrain. Also a sensor should not be in more than one cluster in a network divided into independent sets of sensors, so that each data transmitted to a gateway is unique. Especially in rural environments it is hard to estimate the range of a gateway, therefore it is difficult to determine optimum locations for gateways.

In order to formulate the problem as an MIP instance, all the definitions done in the statement of the problem must be expressed mathematically. Table 1 shows variables used throughout the development of the proposed model.

In the proposed technique, a grid based approach

Table 1: Variables used in MIP formulation.

variable	description
G	grid representation of the terrain
S	set of sensors in the network
N	number of sensors in the network
R	gateway coverage range
r_{grid}	scale of the grid (resolution)
lon_i, lat_i	projected coordinates of the i^{th}
x_i, y_i	grid coordinates of the i^{th} node
s_x, s_y	grid coordinates of sensor $s \in S$

is used to model the environment. Scale of the grid is provided as a parameter, which indicates the number of potential placement location in a single axis. According to the grid scale, resolution of the grid can be determined. Grid resolution indicates the total number of potential placement locations in the terrain. Grid resolution has a significant role in the performance of the optimization model. A change in the resolution of the grid effects the run-time performance of the optimization model.

$$x_i = r_{grid} \cdot \frac{\text{lon}_i - \text{lon}_{min}}{\text{lon}_{max} - \text{lon}_{min}} \tag{1}$$

$$y_i = r_{grid} \cdot \frac{\text{lat}_i - \text{lat}_{min}}{\text{lat}_{max} - \text{lat}_{min}} \tag{2}$$

$$\text{lon}_i = \frac{(\text{lon}_{max} - \text{lon}_{min}) \cdot x_i}{r_{grid}} + \text{lon}_{min} \tag{3}$$

$$\text{lat}_i = \frac{(\text{lon}_{max} - \text{lon}_{min}) \cdot x_i}{r_{grid}} + \text{lon}_{min} \tag{4}$$

Sensor location data should be provided following the format of projected coordinate system. Conversion from projected coordinate system to grid coordinate system is performed by using the Equations 1 and 2. The conversion is performed by scaling each coordinate between the minimum and maximum values among the coordinates following the resolution of the grid. Even though the conversion is straightforward (for instance it does not take earth's curvature into account), it still produces admissible results as seen in the section 4.2.

After the optimization, selected gateway coordinates than converted back to the real coordinates using the Equations 3 and 4 which are the inverse functions of the conversion functions Equation 1 and Equation 2.

Main purpose of the MIP based optimization model is to deploy least gateway device as possible while guaranteeing the sensor network is fully covered by these gateways. The model divides the wireless sensor network into clusters such that in each cluster there is only one gateway and all the sensors in the cluster are connected only to this gateway device. In other words, in the end it is expected to see that there is a one-to-many relation between sensors and gateways.

Equation 5 shows the objective function for the optimization model. A 2-dimensional boolean array (G) is used to represent the grid. Rows and columns of the array indicate the placement location of a gateway. According to the representation, if the gateway is placed at a point, corresponding value in the array G will be *True* (1), otherwise *False* (0). Thus, we can formulate the objective of minimizing the number of gateway as minimizing the number of 1s in G. To be more precise, summation of the entities in the array must be reduced as much as possible.

$$\text{minimize} \sum_{i=0}^{N-1} \sum_{j=0}^{N-1} G_{ij} \tag{5}$$

During the optimization, the aim is to cover all the sensors in the network by the planted gateways. Also each sensor should be connected to only one gateway device. Therefore a constraint for each sensor is defined in the optimization model.

In the expression of the constraint shown in Equation 6, 2D binary array G, is used with a function f (in Equation 7), where the distance between the sensor and the potential gateway location is calculated. According to the calculated distance a Boolean value is returned, which indicates if the sensor is in the range of a gateway device or not. Euclidean Distance formula in Equation 8 is used in order to calculate the distance between devices.

$$\forall (s \in S) \left(\sum_{i=0}^{N-1} \sum_{j=0}^{N-1} G_{ij} \cdot f(i, j, s_x, s_y) \leq 1 \right) \tag{6}$$

$$f(x_i, y_i, x_j, y_j) = \begin{cases} 1 & E(x_i, y_i, x_j, y_j) \leq R \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

$$E(x_i, y_i, x_j, y_j) = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \tag{8}$$

Implementations related to MIP formulation are done by using Python programming language. A library called Python-MIP (Santos and Toffolo, 2020) is used to built an optimization model. Python-MIP is a tool, in which a mixed-integer programming based optimization model is used to formulate the problem and solve it. To visualize the outcomes of the optimization, matplotlib (Hunter, 2007), a commonly used tool to visualize data, is used. Codes of the model definition and visualizations are shared within a repository[1].

[1]https://github.com/canbatuhan/gp-mip

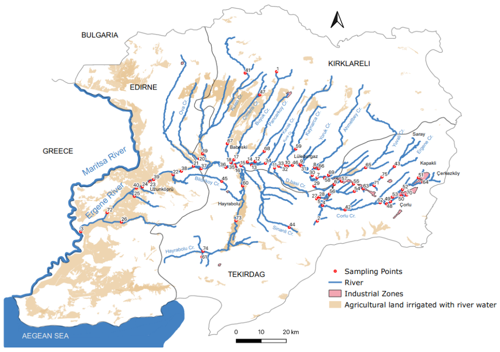


Figure 2: Initial collection of measurements from 75 sample locations on the Ergene watershed. (The image is a courtesy of TUBITAK project 115Y064.

4 EVALUATION

4.1 Experimental Environment

Simulation of the introduced model is performed by using data obtained from a real-world study case. Location of the sensors placed in Ergene river are taken as inputs of the optimization model, in the form of projected coordinate system. Later, the river is modelled as a grid by converting the input data to grid coordinate system, as mentioned in Section 3.2.

Sensor network locations in Ergene River contains 75 sensors spread on a 12000 km^2 area (see Figure 2). Number of gateways to cover all the sensors differs related to the coverage distance, which is the maximum distance for a device to transmit data successfully.

In our simulations, we use Network Simulator 3 (ns-3) (Riley and Henderson, 2010). ns-3 supports third-party modules and for this study, a LoRaWAN module developed by researchers in a previous study is utilized (Magrin et al., 2017). In our simulations, we use a scheduling approach similar to slotted ALOHA to distribute sensors across duty-cycles with as little collision as possible. ns-3 also supports simulating the network under realistic path-loss conditions which are also taken from previous studies and fed into the simulation (Phaiboon and Somkuarnpanit, 2006). For 100 meter, path-loss exponent is found around 2.2 with path-loss as 78 dB.

We also use another simulator, LoRaPlan (Loh et al., 2021b), which is a gateway placement planning software for LoRa enabled sensor networks. In LoRaPlan, a user is able to run simulations with sensor location and gateway location data. Received Signal Strength Indication (RSSI) level of each reachable sensor can be extracted. In LoRaPlan interface, thresholds for RSSI levels can be set and they are set to -120 dBm (lower threshold) and -100 dBm (upper threshold) in default, therefore these threshold values are used in our experiments.

4.2 Evaluation and Discussion

Evaluation of the proposed methods are performed using different measures. Manual placement of gateways is used as a baseline during the comparison of the proposed approaches. Firstly, the number of gateways is compared. Secondly, a measure called Failed Packet Attempt (FPA) ratio (as percentage to all packet transmissions attempts of a sensor) of each gateway placement scenario is extracted from the results of ns-3. Thirdly, by using LoRaPlan, RSSI (dBm) value of each reachable sensor is calculated for different coverage distances ranging from 1000 meters to 10000 meters. Finally, in order to see the differences between proposed approaches, gateway placements are shown on map.

Figure 3a shows how many gateways are used in order to cover all the sensors located in Ergene River. In all methods, the number of gateways decreases as the range increases. Specially in MIP formulation the decline of gateway count is immense and constant. This is because the main objective of the optimization model is to minimize the number of gateways and the formulation in Equation 5. Also in coverage intersection method, gateway count declined in short and long ranges. However, it did not change when the coverage distance is 6000 to 8000 meters. Also as expected, the comparison results shows that placing gateways manually is inefficient in term of the total of number of gateways, since it can be seen that even when the range is 10000 meters, 40 gateway locations are selected in manual placement, whereas 27 gateways are used in coverage intersection method and 14 gateway location is proposed in MIP formulation.

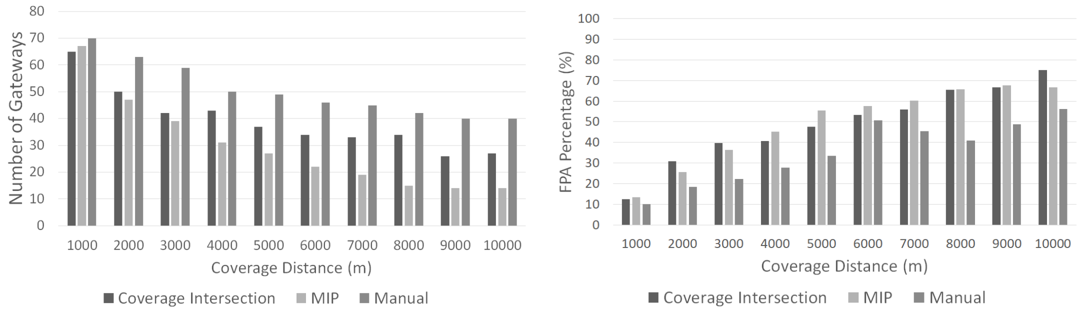
Figure 3b indicates the probability of a packet loss during a transmission considering the proposed gateway placement. FPA percentage for every method increase, while the coverage distance increases. As expected, the manual placement is the best approach to have a network with less transmission failures. Nonetheless, it is important to remember that within the manual placement, the number of gateways is the highest among proposed approaches. In small ranges such as 1000 to 3000 meters; MIP method ends up with finer FPA percentages than coverage intersection method. For an example in the scenario, in which the range is 2000 meters, FPA percentage of MIP formulation is approximately 25,63%, whereas the FPA percentage of coverage intersection methods is 30,83%. In medium ranges, FPA percentage of Coverage Intersection method is less than the proposed optimization model. For long ranges; gateway placement proposal of the MIP method performs better than coverage intersection approach.

In figures 4a and 4b; distribution of RSSI values of the reachable sensors for each gateway placement is compared. Comparisons are done for coverage distances of 2000 meters and 8000 meters, respectively. In other words, behaviour of the introduced methods and the base case are analyzed in terms of short and long ranges of coverage. In all comparisons -100 dBm is selected as an upper threshold, whereas the -120 dBm is selected as a lower threshold as they set as default in simulation software, LoRaPlan.

Figure 4a shows the distributions of RSSI values for reachable sensors in a short range of coverage, where the coverage is 2000 meters. All the distributions indicate that after each gateway placement provided by the proposed methods, strength of the sensors are above the upper threshold. Moreover, it is noticeable that coverage intersection method ends up with RSSI values which are similar to the manual placement, whereas the number of gateways for coverage intersection much less than the manual placement for 2000 meters as shown in Figure 3a.

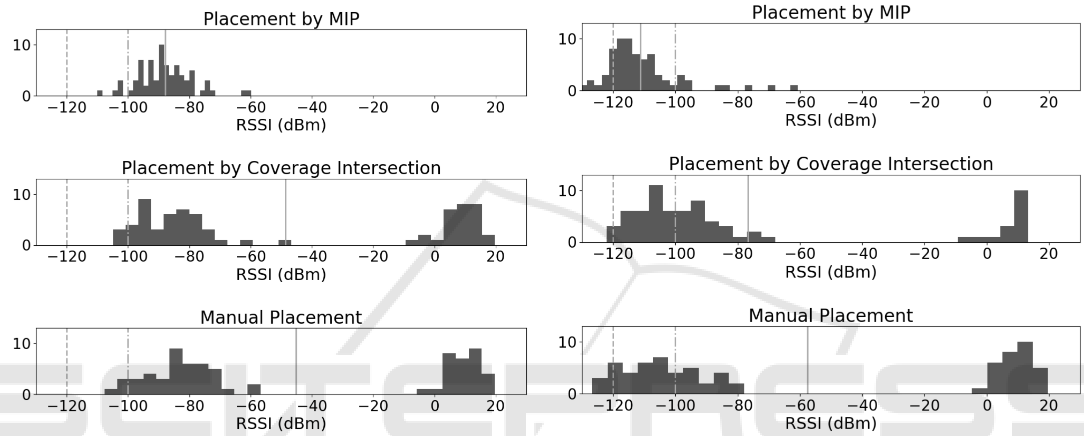
Distributions of RSSI values in long range scenario, where the coverage distance is 8000 meters, are presented in Figure 4b. In terms of MIP formulation, results show that signals strengths are between upper and lower thresholds. Also in this scenario, MIP formulation ends up with signals that their strengths are below the lower threshold which means there are no signal. As it mentioned previously, this is because that the number of gateways is reduced significantly in MIP formulation, specially in long range coverage cases. Figure3a shows that for 8000 meters range, the number of gateways used in the MIP formulation is less than half the gateways used in the coverage intersection method and approximately one third the gateways used in manual deployment. Therefore the distances between gateway and sensors are greater in MIP formulation, thus signal strengths are low.

On the other hand, distribution of RSSI values with gateway deployment by coverage intersection differ from the one with manual placement. In coverage intersection method, RSSI values are mostly between lower threshold and a bit above the upper threshold. Also there is a group of sensors receiving signals that their strengths are very high, in coverage intersection method. However, in manual placement of gateways, some of the signals are below the lower threshold. Also in manual placement, there is a bigger group of sensors that their signal strengths are very high like in coverage intersection method. In overall, coverage intersection method protects its stability in



(a) Comparison for full coverage. (b) Comparison of failed packet attempt ratios.

Figure 3: Comparison among placement methods.



(a) 2000 meters. (b) 8000 meters.

Figure 4: Distribution of RSSI values for reachable sensors.

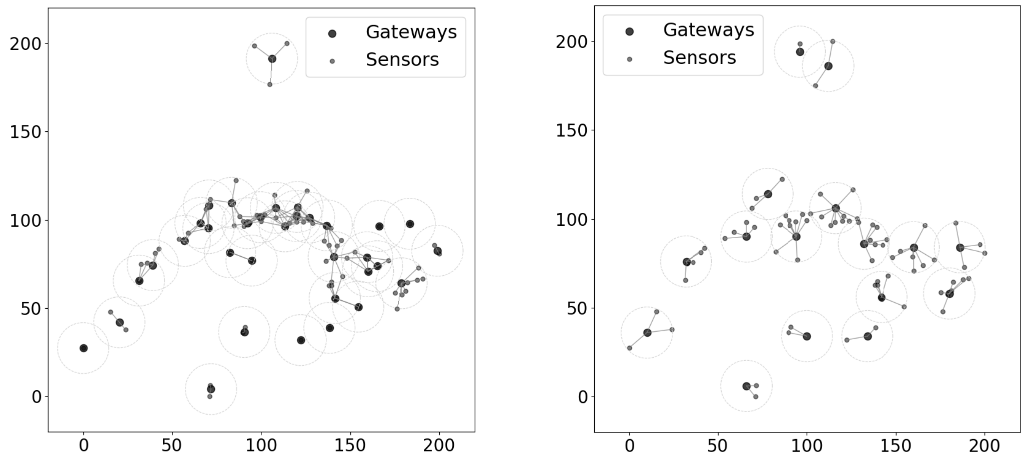
terms of RSSI values, even though the distance is increased. It is also remarkable that the number of gateways used in coverage intersection method is much less than manual placement.

Finally, in order to make a comparison between the results of MIP formulation and coverage intersection method, the sensor network and the proposed gateway locations are visualized on a grid. Also the coverage distances and connections between devices are shown within the network. In Figures 5a and 5b, gateway placements for 8000 meters of coverage distance are visualized.

After the gateway placement by coverage intersection for 8000 meters of coverage distance, 34 gateways are used to cover all the sensors in the network as shown in Figure 5a. However, there are some locations in the network that a single gateway might be deployed, so that multiple sensors can be covered. Thus, the model does not reduce the number gateways as possible. Moreover, a sensor might be in the range of more than one gateways. On the other hand, performance of the model is better than MIP formulation in term of overall signal strength as it shown in Figures 4a and 4b.

Gateway placement done by MIP formulation is focused on minimizing the number of gateways to fully cover the network. Figure 5b shows that the proposed optimization model, selects 15 gateway locations to cover all the sensors. This means that MIP formulation reduces the number of gateways more than half of the gateways used in coverage intersection method. Also it is noticeable that the model results with gateway placements, so that all the sensors in the network are connected to a single gateway. Reducing the number of gateways causes a decline in signal strengths as indicated in Figures 4a and 4b, since distances between devices increase. However, Figure 3b shows that the FPA percentages of placement by MIP formulation are similar to Coverage Intersection method.

While forming the clusters, transmission range of gateway devices is the first consideration of the proposed approach. Also minimizing the number of gateways is the main objective of the optimization model. In the end, the offered model provides a set of placement locations, which covers the whole net-



(a) Placement by coverage intersection. (b) Placement by MIP formulation.

Figure 5: Gateway placement examples.

work while the number of gateway devices decreases and partition the network into clusters having a certain level of quality of data measurement.

A caveat for the introduced technique is that the experimental environment is a rural area. Topology of the terrain has a crucial role in data transmission between devices. Even though LoRa provides a higher distance of coverage compared to other techniques, due to the geographical obstacles, range of a signal might differ. For example, if there is a hill between two devices, data transmission might not be completed successfully, despite to the fact that these two devices are very close to each other.

5 CONCLUSION

This paper presents two different gateway placement approaches and evaluates these approaches over a real-world sensor positions in Ergene River. We run our simulations in ns-3 and LoRaPlan simulators to investigate the communication quality obtained by the network. Our results provide numerical guides to examine the trade-off between using less gateways to cover the full set of sensors versus communication quality.

This work can be extended by experimenting on different sensor position distributions to further investigate the points where each of the proposed approaches' perform poorly. Moreover, MIP formulation and optimization presented in the paper can be investigated under different grid sizes to discover the effect of using finer resolutions in the optimization versus time requirements. Finally the proposed placement strategies may also have some additional constraints such as ease of transportation to gateways or terrain information such as vegetation, etc.

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